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STUDY OF A CONCRETE COLUMN FOR STABILITY UNDER ASYMMETRIC CORROSION

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Abstract. Reinforced concrete became widespread due to its many positive properties: durability, fire re-sistance, resistance to corrosive effects, high resistance to static and dynamic loads, low operating costs for maintaining buildings and structures, and relative cheapness of manufacturing. The presence of widespread large and small aggregate used in the production of reinforced concrete makes it applicable in all corners of the globe and even beyond its borders. The emergence and development of building structures, including reinforced concrete, is inextricably linked to the conditions of the material life of society, the development of productive forces. The appearance of reinforced concrete coincides with the period of accelerated development of industry, transport and trade in the second half of the 19th century. The period of emergence of reinforced concrete (1850-1885) is characterized by the appearance of the first structures made of reinforced concrete in France (Lam-bo, 1850; Quancier, 1854; gardener Monier, 1867-1880), England (Wilkinson, 1854), the USA (Hiatt, 1855-1877).

Buildings and structures and their structures during operation experience force and non-force effects of the environment. With a symmetrical effect of the medium, centrally compressed rods remain centrally compressed, and with an extracentral one, extracentric eccentricity appears. First, the rod experiences off-center compression. Further deformation will lead the rod to longitudinal bending, and under the action of a transverse load to longitudinal-transverse bending.

In steel structures, the environment causes corrosion, in concrete – corrosion and neutralization. In a physically linear formulation, these problems are solved, but it is necessary to take into account the real diagrams of steel and concrete, and to solve problems according to an unformed deformed scheme. Given the impact of the environment, new challenges arise with constructive and induced heterogeneity. Noncentrally compressed elements are part of statically definable and indeterminate structures: these are beams, threehinge systems, frames and trusses.

This is a new topic, a new formulation of the question, tasks that require the development of new methods.

Keywords: spatial stability, longitudinal force and torque, impact of an aggressive environment, corrosion.

ДОСЛІДЖЕННЯ БЕТОННОЇ КОЛОНИ НА СТІЙКІСТЬ ПРИ НЕСИМЕТРИЧНОМУ ВПЛИВУ КОРОЗІЇ

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Анотація. Розповсюдження залізобетон одержав унаслідок багатьох його позитивних властивостей: довговічності, вогнестійкості, опору корозійним впливам, високому опору статичним і динамічним навантаженням, малих експлуатаційних витрат на утримання будинків і споруд, відносної дешевизни виготовлення. Найявністю розповсюдженого великого і дрібного заповнювача, що йде на виготовлення залізобетону, робить його застосовним у всіх куточках земної кулі і навіть за її межами. Виникнення і розвиток будівельних конструкцій, у тому числі залізобетонних, нерозривно пов'язано з умовами матеріального життя суспільства, розвитком продуктивних сил. Поява залізобетону збігається з періодом прискороного розвитку промисловості, транспорту й торгівлі в другій половині ХІХ ст. Період виникнення залізобетону (1850-1885 рр.) характеризується появою перших конструкцій з армованого



бетону у Франції (Ламбо, 1850 р.; Куаньє, 1854; садівник Моньє, 1867-1880 рр.), Англії (Уїлкінсон, 1854 р.), США (Гіатт, 1855-1877 рр.).

Будівлі та споруди та їх конструкції в період експлуатації відчують силові та не силові впливи навколишнього середовища. При симетричному впливі середовища центрально стислі стрижні залишаються центрально стиснутими, а при позацентровому з'являється позацентровий ексцентриситет. Спочатку стрижень відчуває позацентрове стиск. Подальша деформація приведе стрижень до поздовжнього вигину, а при дії поперечного навантаження до поздовжньо-поперечного вигину.

У сталевих конструкціях середовище викликає корозію, у бетонних – корозію та нейтралізацію.

У фізично лінійній постановці ці завдання вирішені, але необхідно врахувати реальні діаграми сталі та бетону, і вирішувати завдання за неформованою деформованою схемою. З урахуванням впливу середовища виникають нові завдання з конструктивною і наведеною неоднорідністю. Нецентренно стислі елементи входять до складу статично визначних і невизначених конструкцій: це балки, тришарнірні системи, рами та ферми. Для них потрібно розробляти методику розрахунку.

Це нова тема, нова постановка питання, завдання, що потребують розробки нових методик.

Ключові слова: просторова стійкість, поздовжня сила, ексцентриситет, вплив агресивного середовища, корозія.

1 INTRODUCTION

In the process of operation, buildings and structures are affected by the external environment for a long time and, as an example, corrosion. This greatly complicates the durability and functionality of objects.

2 ANALYSIS OF LITERARY DATA AND PROBLEM STATEMENT

When studying the spatial stability of frames, it is necessary to take into account not only the effect of compressive longitudinal forces on structural elements, but also torques. The problems of loss of stability of rods under the action of torques, as well as under the joint action of longitudinal forces and torques, were considered earlier, but cases of constant length cross-sections, i.e. constant bending stiffnesses, were considered. A similar problem for a rod of constant cross-section is considered in the [1–13]. Analysis of recent studies or publications. The need to consider the cases of variable cross-sections when taking into account the impact of an aggressive environment on reinforced concrete structures is explained by the fact that the depth of the damaged zone depends on the abscissa x cross-section of the rod [2,3]

$$h(x,t) = h_0 e^{-\beta v_0 / [l_0(t) - x]}, \quad (1)$$

In here $l_0(t) = v_0 t$ – corroded length (t – column operating time in years). Parameter values h_0, β and v_0 depend on the type and intensity of the aggressive environment [3].

When calculating non-centrally compressed concrete elements, it is necessary to take into account the random eccentricity of the longitudinal force due to factors not taken into account in the calculation, including the heterogeneity of the properties of concrete in cross-section. For elements of statically indeterminate structures (for example, pinched at the ends of walls or pillars), the value of the eccentricity of the longitudinal force relative to the center of gravity of the reduced section is taken to be equal to the eccentricity value obtained from the static calculation of the structure. In the elements of statically determined structures, eccentricity is found as the sum of eccentricities—determined from a static calculation of a structure and a random one. The main purpose of these restrictions is to prevent the use of elements whose bearing capacity would be provided only by stretched concrete, since with any accidental crack, the balance of forces in the cross-section is disturbed. An exception can be made in some cases for structures working on compression with higher values of eccentricities (as well as for bendable structures), when their destruction does not pose an immediate danger to human life and the safety of equipment (for example, elements lying on a solid base, etc.). The main one for non-centrally compressed concrete elements is the calculation of the strength of the compressed zone without taking into account the resistance of concrete to the stretched zone. The resistance of concrete to compression is represented by stresses equal to Ph , evenly distributed over the part of the actual compressed zone, which is conventionally called "compressed" [4].

3 PURPOSE AND OBJECTIVES OF THE RESEARCH

The purpose of the study is to determine the stability conditions of a reinforced concrete rod (column) of variable cross-section under the action of compressive longitudinal force. To achieve this goal, you need to solve the following tasks: First, it is necessary to divide the corroded part of the column into a series of sections with a cross-section constant in length. Thus, the column appears to be a system of sections with a cross-section constant in length of each section, rigidly connected to each other. Secondly, it is necessary to determine at each

site additional bending moments caused by the action of torque. Next, it is necessary to determine the given moments of inertia of the cross-section with respect to the main central axes of the cross-section and to draw up differential equations of spatial bending for each section of the column. The solution of each of these equations is a linear combination of trigonometric functions.

4 RESEARCH RESULTS

As an example of stability research, consider a concrete column of rectangular cross-section, rigidly pinched in the ground. The column will be exposed to asymmetrical corrosion. The lower section of the side face of the column will be subjected to corrosion (Fig. 1). The cross-section in the lower section is shown in Fig. 2, where C is the center of intact cross-section, C1 is the center of the intact part of the corroded section). The upper edge of the corrosion zone will move upwards at a constant rate v_0 .

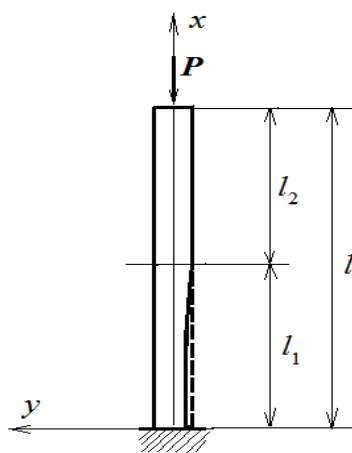


Fig. 1. Column under the influence of corrosion

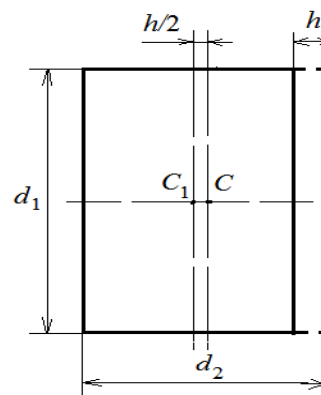


Fig. 2. Column cross-section

The depth of the damaged area is determined by the formula:

$$h(t_1) = h_0 e^{-\beta/t_1} . \tag{1}$$

Here t_1 is the time counted from the moment t_0 of the beginning of the corrosion process in a given cross-section of the rod. Obviously

$$t_0 = \frac{x}{v_0} . \tag{2}$$

Taking into account (2), the formula (1) takes the following form:

$$h(x, t) = h_0 e^{-\beta/(t-x/v_0)} , \tag{3}$$

(x – abscissa cross-section). Here t is the time counted from the beginning of the corrosion process in the column. Since the length l_1 of the first (corroded) section of the column is

$$l_1(t) = v_0 t ,$$

then formula (3) can be written as:

$$h(x, t) = h_0 e^{-\beta v_0/[l_1(t)-x]} . \tag{4}$$

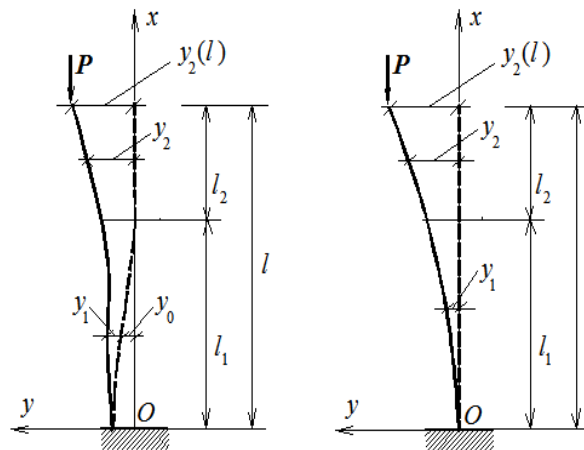


Fig. 3. Location of transverse force centers

In Fig. 3, the dashed line shows the axis on which the centers of the cross-sections of the intact part of the column are located. A solid line shows the deformed position of this axis. Through y_1 are the ordinates of the movements of the axis points in the first (lower) section, and y_0 is equal to the distance of CC_1 in each section, i.e.

$$y_0 = \frac{h(x,t)}{2}. \quad (5)$$

The resulting stress-strain state of the column can be considered as a longitudinal bend of the rod with the initial curvature of the axis. Following [2] we make a differential equation for the first section:

$$EJ_1 \frac{d^2 y_1}{dx^2} = P[y_2(l,t) - y_1 - y_0] \quad (0 \leq x \leq l_1). \quad (6)$$

The moment of inertia of the cross-section J is determined by the formula:

$$J_1(x,t) = \frac{d_1[d_2 - h(x,t)]^3}{12}, \quad (7)$$

(d_1 and d_2 are the width and height of the cross-section at $t = 0$). Note that time t plays the role of a parameter in equation (6). For the second (upper) section of the column, we have the following differential equation:

$$EJ_2 \frac{d^2 y_2}{dx^2} = P[y_2(l,t) - y_2] \quad (l_1 \leq x \leq l), \quad (8)$$

where is $J_2 = d_1 d_2^3 / 12$.

Note that the values of the critical forces are determined from the condition for the existence of a non-zero solution in a system consisting of the equation:

$$EJ_1 \frac{d^2 y_1}{dx^2} = P[y_2(l,t) - y_1] \quad (0 \leq x \leq l_1) \quad (9)$$

and equations (8) under the following conditions:

$$y_1(0,t) = 0, \frac{dy_1}{dx}(0,t) = 0, y_2(l_1,t) = y_1(l_1,t), \frac{dy_2}{dx}(l_1,t) = \frac{dy_1}{dx}(l_1,t). \quad (10)$$



Let's replace the independent variable in equation (9) $\xi = x/l$ (l – column height). As a result, we get the following equation:

$$\frac{d^2 y_1}{d\xi^2} + \varepsilon f(\xi, t) y_1 = \varepsilon f(\xi, t) D, \quad (11)$$

where is

$$\varepsilon = \frac{Pl^2}{E_0}, \quad f(\xi, t) = \frac{12}{d_1[d_2 - h(\xi, t)]^3}, \quad D = y_2(1, t), \quad (12)$$

$$h(\xi, t) = h_0 e^{-\beta v_0 / l [\lambda_1(t) - \xi]}, \quad \lambda_1(t) = \frac{l_1(t)}{l}.$$

Let's approximate the function $f(\xi, t)$ per segment $0 \leq \xi \leq \lambda_1(t)$ polynomial using The Lagrange interpolation formula [3]:

$$f(\xi, t) = \sum_{i=0}^n f(\xi_i, t) \frac{\omega_i(\xi)}{\omega_i(\xi_i)}, \quad (13)$$

$$\omega_i(\xi) = (\xi - \xi_1)(\xi - \xi_2) \dots (\xi - \xi_{i-1})(\xi - \xi_{i+1}) \dots (\xi - \xi_n),$$

$$\left(\xi_i = \frac{\lambda_1}{n} i, \quad i = 0, 1, \dots, n \right).$$

Imagine $\omega_i(\xi)$ ($i = 0, 1, \dots, n$) as follows:

$$\omega_i(\xi) = \sum_{j=0}^n b_{i,j} \xi^j, \quad (14)$$

where is $b_{i,j}$ ($i, j = 0, 1, \dots, n$) – constant coefficients, unambiguously expressed through ξ_i ($i = 0, 1, \dots, n$).

Substituting the representation (14) into formula (13), we get:

$$f(\xi, t) = \sum_{j=0}^{\infty} f_j(t) \xi^j, \quad (15)$$

where is :

$$f_j(t) = \sum_{i=0}^n f(\xi_i, t) \frac{b_{i,j}}{\omega_i(\xi_i)} \quad (j = 0, 1, \dots, n), \quad f_j(t) = 0 \quad (j > n).$$

We will look for a solution $y_1(\xi, t)$ Cauchy's problems for equation (11) under initial conditions:

$$y_1(0, t) = 0, \quad \frac{dy_1(0, t)}{d\xi} = 0 \quad (16)$$

in the form of decomposition by degrees of a small parameter ε :

$$y_1(\xi, t) = \sum_{k=0}^{\infty} \varepsilon^k y_{1,k}(\xi, t) \quad (17)$$

and assume that the conditions (16) are met for each of the functions $y_{1,k}(\xi, t)$ ($k = 0, 1, 2, \dots$).

Substituting this decomposition into equation (11), we obtain:



$$\frac{d^2 y_{1,0}}{d\xi^2} + \sum_{k=1}^{\infty} \varepsilon^k \left[\frac{d^2 y_{1,k}}{d\xi^2} + f(\xi, t) y_{1,k-1} \right] = \varepsilon f(\xi, t) D. \quad (18)$$

Equating the coefficients at degrees ε zero, we get a system of differential equations:

$$\begin{aligned} \frac{d^2 y_{1,0}}{d\xi^2} &= 0, \quad \frac{d^2 y_{1,1}}{d\xi^2} = Df(\xi, t) - f(\xi, t) y_{1,0}, \\ \frac{d^2 y_{1,k}}{d\xi^2} &= -f(\xi, t) y_{1,k-1} \quad (k > 1). \end{aligned} \quad (19)$$

From the first equation (19), taking into account the conditions (16), we get:

$$y_{1,0}(\xi, t) = 0. \quad (20)$$

With $k = 1$, equation (19) given (20) looks like this:

$$\frac{d^2 y_{1,1}}{d\xi^2} = Df(\xi, t). \quad (21)$$

Substituting here (15) and integrating ξ twice, we find:

$$y_{1,1}(\xi, t) = D \sum_{j=0}^{\infty} f_j^{(1)} \xi^j, \quad (22)$$

where is

$$f_0^{(1)} = f_1^{(1)} = 0, \quad f_j^{(1)} = \frac{f_{j-2}}{(j-1)j} \quad (2 \leq j \leq n+2), \quad f_j^{(1)} = 0 \quad (j > n+2).$$

At $k = 2$, using the decompositions (15) and (22), we get:

$$\frac{d^2 y_{1,2}}{d\xi^2} = -D \sum_{j=0}^{\infty} f_j(t) \xi^j \sum_{i=0}^{\infty} f_i^{(1)} \xi^i. \quad (23)$$

Multiplying the power series standing in the right part (23) and integrating ξ twice taking into account the conditions (16), we come to the following expression:

$$y_{1,2}(\xi, t) = D \sum_{j=0}^{\infty} f_j^{(2)} \xi^j, \quad (24)$$

where is

$$f_0^{(2)} = f_1^{(2)} = 0, \quad f_j^{(2)} = \frac{1}{(j-1)j} \sum_{m=0}^{j-2} f_m f_{j-m-2}^{(1)} \quad (j \geq 2).$$

Note that a fairly rapid decrease in coefficients $f_j^{(2)}$ with an increase in j and the need to calculate the sum of the series when $\xi < 1$ in the first section, it is possible to limit the calculation of a small number of coefficients of the series (24). We do exactly the same thing when $k > 2$. As a result, we obtain recurrence ratios:

$$f_0^{(k)} = f_1^{(k)} = 0, \quad f_j^{(k)} = \frac{1}{(j-1)j} \sum_{m=0}^{j-2} f_m f_{j-m-2}^{(k-1)} \quad (k \geq 2, j \geq 2)$$

for decomposition coefficients:



$$y_{1,k}(\xi, t) = D \sum_{j=0}^{\infty} f_j^{(k)} \xi^j \quad (k = 2, 3, \dots). \quad (25)$$

In view of the considerable smallness of the ε for practical tasks, it is possible to limit oneself to a small number of members in the decomposition (17). Thus, it can be considered that the private solution $y_1(\xi, \varepsilon, t)$ Cauchy's problem for equation (11) given conditions (16) is constructed. It follows from (22), (24) and (25) that it can be presented in the following form:

$$y_1(\xi, t) = DZ_1(\xi, t), \quad (26)$$

where is:

$$Z_1(\xi, t) = \sum_{k=1}^{\infty} Z_{1,k}(\xi, t) \varepsilon^k, \quad Z_{1,k}(\xi, t) = \sum_{j=0}^{\infty} f_j^{(k)} \xi^j.$$

Let's move on to the second (not subject to corrosion) section. Differential equation (9) after substitution $\xi = x/l$ will look like this:

$$\frac{d^2 y_2}{d\xi^2} + k_2^2 y_2 = k_2^2 D, \quad (27)$$

where is:

$$k_2 = l \sqrt{\frac{P}{EJ_2}}, \quad J_2 = \frac{d_1 d_2^3}{12}, \quad D = y_2(1).$$

General solution of this equation:

$$y_2(\xi, t) = C_1 \cos k_2 \xi + C_2 \sin k_2 \xi + D, \quad (28)$$

(C_1 and C_2 are arbitrary constants that depend on the parameters t and P . To find these constants, we use the third and fourth conditions (10):

$$y_2(\lambda_1(t), t) = y_1(\lambda_1(t), \varepsilon, t), \quad y_2'(\lambda_1(t), t) = y_1'(\lambda_1(t), \varepsilon, t), \quad (29)$$

(the stroke denotes the derivative of ξ , $\lambda_1(t) = l_1(t)/l$).

From (29) we get a system of equations:

$$\begin{aligned} C_1 \cos k_2 \lambda_1(t) + C_2 \sin k_2 \lambda_1(t) &= D[Z_1(\lambda_1(t), t) - 1], \\ k_2 [-C_1 \sin_2 \lambda_1(t) + C_2 \cos k_2 \lambda_1(t)] &= DZ_1'(\lambda_1(t), t), \end{aligned} \quad (30)$$

solving which we find:

$$C_1 = \frac{D}{k_2} F_1(P, t), \quad C_2 = \frac{D}{k_2} F_2(P, t),$$

where is:

$$\begin{aligned} F_1(P, t) &= [Z_1(\lambda_1(t), t) - 1] k_2 \cos k_2 \lambda_1(t) - Z_1'(\lambda_1(t), t) \sin k_2 \lambda_1(t), \\ F_2(P, t) &= [Z_1(\lambda_1(t), t) - 1] k_2 \sin k_2 \lambda_1(t) + Z_1'(\lambda_1(t), t) \cos k_2 \lambda_1(t). \end{aligned} \quad (31)$$

Substituting the resulting expressions in (28), we will have:

$$y_2(\xi, t) = \frac{D}{k_2} [F_1(P, t) \cos k_2 \xi + F_2(P, t) \sin k_2 \xi]. \quad (32)$$

Recall that:

$$D = y_2(1, t). \tag{33}$$

Substituting here (32), we will have:

$$D[F_1(P, t) \cos k_2 + F_2(P, t) \sin k_2 - 1] = 0$$

and since $D \neq 0$, that:

$$F_1(P, t) \cos k_2 + F_2(P, t) \sin k_2 - 1 = 0. \tag{34}$$

This is the equation of critical forces.

Proceed to the determination of the deflections of the column under the action of the longitudinal force P . Let's make a substitution in equation (6) $\xi = x/l$. As a result, we get the following equation:

$$\frac{d^2 y_1}{d\xi^2} + \varepsilon f(\xi, t) y_1 = \varepsilon Df(\xi, t) - \varepsilon g(\xi, t). \tag{35}$$

In here $g(\xi, t) = 6h(\xi, t)/d_1[d_2 - h(\xi, t)]^3$. Like the function $f(\xi, t)$, approximate the function $g(\xi, t)$ per segment $0 \leq \xi \leq \lambda_1(t)$ an interpolated Legendre polynomial. As a result, we get:

$$g(\xi, t) = \sum_{j=0}^{\infty} g_j(t) \xi^j, \tag{36}$$

where is:

$$g_j(t) = \sum_{i=0}^n g(\xi_i, t) \frac{b_{i,j}}{\omega_i(\xi_i)} \quad (j=0, 1, \dots, n), \quad g_j(t) = 0 \quad (j > n).$$

As above, we will look for a solution to $y_1, h(\xi, t)$ of the Cauchy problem for equation (35) under initial conditions (16) in the form of a decomposition by degrees of a small parameter ε :

$$y_{1,p}(\xi, t) = \sum_{k=0}^{\infty} \varepsilon^k y_{1,p,k}(\xi, t). \tag{37}$$

Acting similarly to the above, we obtain:

$$y_{1,p,0}(\xi, t) = 0, \quad y_{1,p,k}(\xi, t) = DZ_1^{(k)}(\xi, t) + Z_2^{(k)}(\xi, t), \tag{38}$$

$$Z_2^{(2)}(\xi, t) = \sum_{j=0}^{\infty} g_j^{(k)}(t) \xi^j,$$

where is:

$$g_0^{(1)} = g_1^{(1)} = 0, \quad g_j^{(1)} = \frac{g_{j-2}}{(j-1)j} \quad (2 \leq j \leq n+2), \quad g_j^{(1)} = 0 \quad (j > n+2),$$

$$g_0^{(k)} = g_1^{(k)} = 0, \quad g_j^{(k)} = -\frac{1}{(j-1)j} \sum_{m=0}^{j-2} f_m f_{j-m-2}^{(k-1)} \quad (k \geq 2, j \geq 2).$$

The desired decision can be written in the following form:

$$y_{1,p}(\xi, t) = DZ_1(\xi, t) + Z_2(\xi, t), \tag{39}$$

where is:

$$Z_2(\xi, t) = \sum_{k=1}^{\infty} \varepsilon^k Z_2^{(k)}(\xi, t).$$

Let's move on to the second section. As above, to find the constants C_1 and C_2 in (28), we use the conditions (29). As a result, we get a system of equations:

$$\begin{aligned} C_1 \cos k_2 \lambda_1(t) + C_2 \sin k_2 \lambda_1(t) &= y_{1,p}(\lambda_1(t), t) - D, \\ k_2 [-C_3 \sin_2 \lambda_1(t) + C_4 \cos k_2 \lambda_1(t)] &= y_{1,p}'(\lambda_1(t), t), \end{aligned} \quad (40)$$

stroke means derivative on ξ , solving which we find:

$$C_1 = \frac{1}{k_2} F_3(P, t), \quad C_2 = \frac{1}{k_2} F_4(P, t),$$

where is:

$$\begin{aligned} F_3(P, t) &= [y_{1,p}(\lambda_1(t), t) - D] k_2 \cos k_2 \lambda_1(t) - y_{1,p}'(\lambda_1(t), t) \sin k_2 \lambda_1(t), \\ F_4(P, t) &= [y_{1,p}(\lambda_1(t), t) - D] k_2 \sin k_2 \lambda_1(t) + y_{1,p}'(\lambda_1(t), t) \cos k_2 \lambda_1(t). \end{aligned} \quad (41)$$

Substituting the resulting expressions in (28), we will have:

$$y_2(\xi, t) = \frac{1}{k_2} [F_3(P, t) \cos k_2 \xi + F_4(P, t) \sin k_2 \xi] + D.$$

We now use equality (33), from which we obtain using (39) and (41):

$$D = - \frac{Z_2(\lambda_1(t), t) k_2 \cos k_2 \lambda_2(t) + Z_2'(\lambda_1(t), t) \sin k_2 \lambda_2(t)}{[Z_1(\lambda_1(t), t) - 1] k_2 \cos k_2 \lambda_2(t) + Z_1'(\lambda_1(t), t) \sin k_2 \lambda_2(t)}. \quad (42)$$

5 DISCUSSION OF RESEARCH RESULTS

When designing and operating buildings and structures, it is necessary to take into account the emerging eccentricity and the non-central action of the force, which increases with prolonged corrosion exposure [14].

6 CONCLUSIONS

A method is proposed that allows to study the stability of concrete rigidly pinched columns at the base with asymmetrical aggressive corrosion effects, which is necessary for their timely strengthening to ensure the reliability of the structure.

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